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Properties of hot residual nuclei produced in pA reactions

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Abstract. The predictions for the production of nuclides and particles in proton-induced reactions are important *e.g.* for the detailed design of spallation neutron sources or accelerator-driven-systems. Computational tools are required that are able to describe quantitatively the two-stage process *i.e.* intra-nuclear cascade followed by evaporation-fission. The first stage is a highly non-equilibrated process in which incoming proton deposits in hot residual nucleus both excitation energy and angular momentum. The CBUU transport model calculation for few targets, for the proton energy range 0.4–2.0 GeV are presented, with the idea to find global parametrizations for the distributions of charge, mass, excitation energy, angular momentum of hot residual nuclei.

PACS. 24.10.-i Nuclear reaction models and methods – 24.10.Lx Monte Carlo simulations (including hadron and parton cascades and string breaking models)

Nowadays neutron beams are produced mainly by fission in nuclear reactors optimized for high neutron brightness. Reactors dedicated to the production of neutron *e.g.* for condensed matter research produce a lot of heat. Its dissipation in the core approached the limits set by up-to-date material technology ($\sim$ 190 MeV of energy dissipated for produced neutron). Future solutions are accelerator-based pulsed sources, see fig. 1. By bombarding heavy metal target with high-energy particles (*e.g.* protons) in a spallation process neutrons are produced with only $\sim$ 30 MeV of energy dissipated for generated neutron. During the last decade several spallation sources (IPNS [1], ISIS [1], LANSCE [2], SINQ [3] became operational. Technical study of 5 MW spallation neutron source is being completed in Germany [4] and its construction is under discussion now.

With the advent of spallation neutron sources there is a growing need for high-energy nuclear transport codes for incident proton energy in the GeV range. The main objective is to simulate what are the distributions of emitted particles (protons, alphas ...) and residual nuclei. Two stages of the reaction have to be suitably described: a) high-energy intra nuclear cascade INC, followed by b) subsequent statistical evaporation-fission process. The second stage of the reaction (statistical evaporation in competition with fission) is rather nonexpensive computationally (many well-checked codes are available).

Fig. 1. Planned accelerator-driven neutron sources.

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However, the first stage it is a highly non-equilibrated process that has to be calculated using state-of-the-art sophisticated methods based, *e.g.*, on the CBUU approach [5, 6]. It would be useful to find a way to perform the first stage of the calculations "cheaply" while still sufficiently exactly. The solution may be to calculate the properties of hot residual nuclei produced during INC stage (*i.e.* the distributions of their mass, charge, excitation energy, angular distribution) for some chosen sample of impact proton energies and targets in order to have the possibility to interpolate for other energies and targets.

The CBUU model describes the propagation and mutual interaction of nucleons, Delta's, N^*-resonances as well as π- and η-mesons. It consists of a set of coupled equations of the one-body phase-space distributions [5,6] which can be solved by means of test particle method (every real particle is substituted by possibly large number of test particles).

In the CBUU calculations the four-momenta of all hadrons are propagated in time, therefore it is a straighforward task to evaluate the distributions of properties of the residual (hot) nuclei (mass, charge, angular momentum, excitation energy). For this purpose one computes, as a function of time, those particles (essentially nucleons) that have left the residual heavy fragment at position $\mathbf{R}$, *i.e.*

$$|\mathbf{r}_i - \mathbf{R}| \geq R_A + 2\,\mathrm{fm}, \tag{1}$$

where $R_A = 1.2\,\mathrm{fm}\ A_{\mathrm{t}}^{1/3}$ denotes the radius of the target with mass number A_{t}. Now let the number of particles emitted be $N_p(t)$. For each parallel ensemble one is able to evaluate then the fragment's average mass number, its excitation energy, three-momentum and angular momentum by exploring the conservation of total energy, mass number, momentum and angular momentum [7]:

$$\begin{aligned}
\langle E^* \rangle(t) &= E_{\mathrm{tot}} - \sum_{j=1}^{N_p(t)} \sqrt{p_j^2 + M_j^2} - M_{\mathrm{res}} - E_{\mathrm{coul}},\\
\langle A_F \rangle(t) &= A_{\mathrm{t}} + 1 - N_p(t),\\
\langle \mathbf{p} \rangle(t) &= \mathbf{P}_{\mathrm{tot}} - \sum_{j=1}^{N_p(t)} \mathbf{p}_j(t),\\
\langle \mathbf{L} \rangle(t) &= \mathbf{L}_{\mathrm{tot}} - \sum_{j=1}^{N_p(t)} \mathbf{r}_j(t) \times \mathbf{p}_j(t).
\end{aligned} \tag{2}$$

In eq. (2) M_{res} denotes the mass of the "residual nucleus", E_{coul} stands for the Coulomb energy between the emitted particles and the "residual nucleus".

All quantities in (2) depend explicitly on time t due to the continuous evaporation of particles from the final compound system. Since the further decay chains will be followed by statistical model codes, the actual transition time for the connection of the CBUU and the statistical model calculation is of no significance as long as the system has left the *nonequilibrium phase* of the reaction and achieved *statistical equilibrium.* It has been checked that it is sufficient to trace the history of each ensemble of events within CBUU up to $150\,\mathrm{fm}/c$ (5×10^{-22} s).

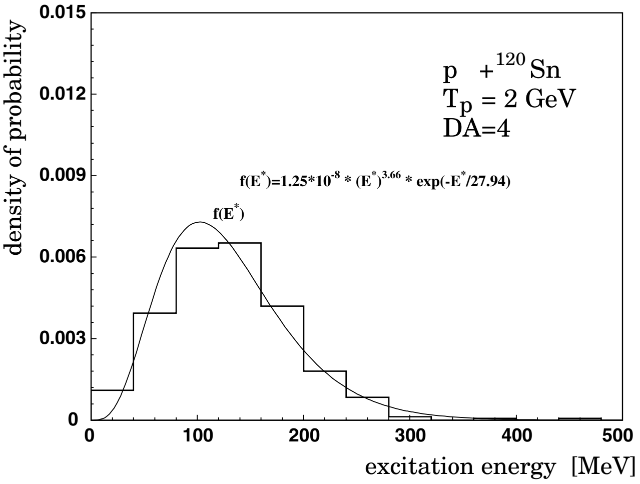

Fig. 2. An example of simulated distribution of excitation energy with imposed on it fitted gamma distribution (solid line).

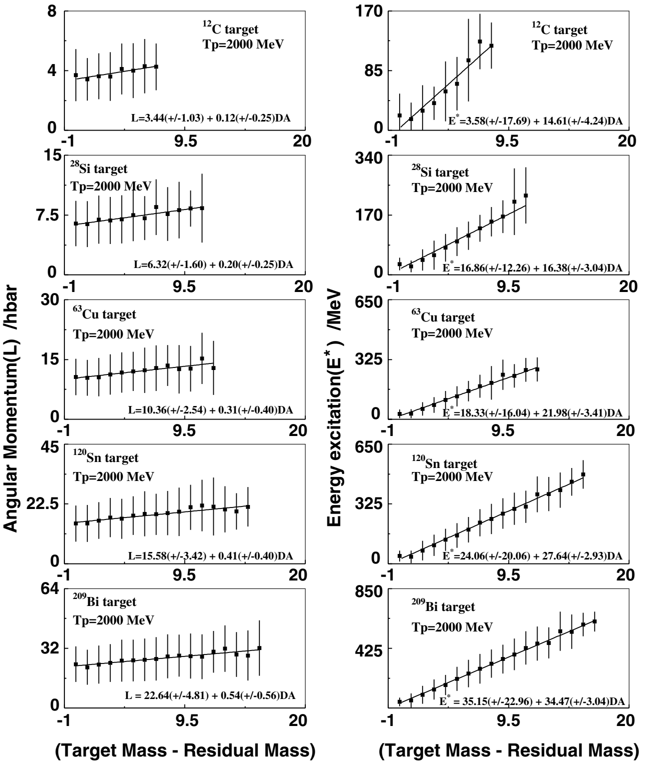

Fig. 3. Left side: calculated in the framework of the CBUU model angular momentum of created hot nuclei (*i.e.* after the INC stage of reaction), for proton incident energy $T_p = 2\,\mathrm{GeV}$, for the following targets: ^{12}C, ^{28}Si, ^{63}Cu, ^{120}Sn, ^{209}Bi. On the abscissa axis the difference DA = Target Mass − Residual Mass is indicated. The full squares denote the average values of angular momentum for a given value of DA, vertical bars show what is the σ parameter (standard deviation) of the distribution of angular momentum for given DA.

The CBUU calculations were performed for proton kinetic energiesin the range 0.4–2.0 GeV, for the following

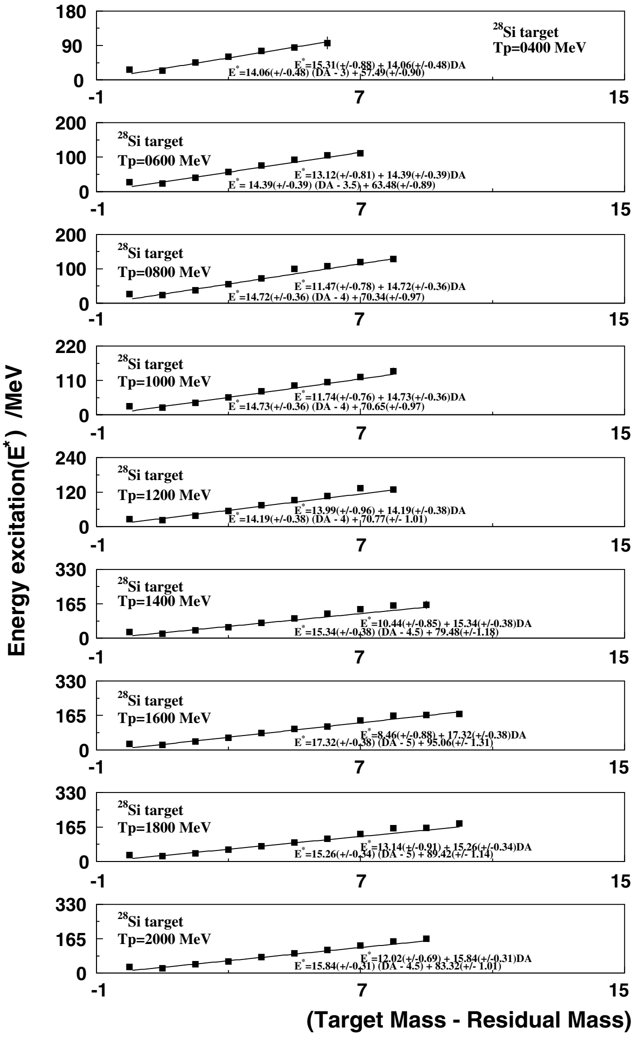

Fig. 4. Average values of excitation energy distributions are presented for proton incident energies $T_p = 0.4$–$2.0\,\mathrm{GeV}$ (full squares), as a function of DA = Target Mass – Residual Mass.

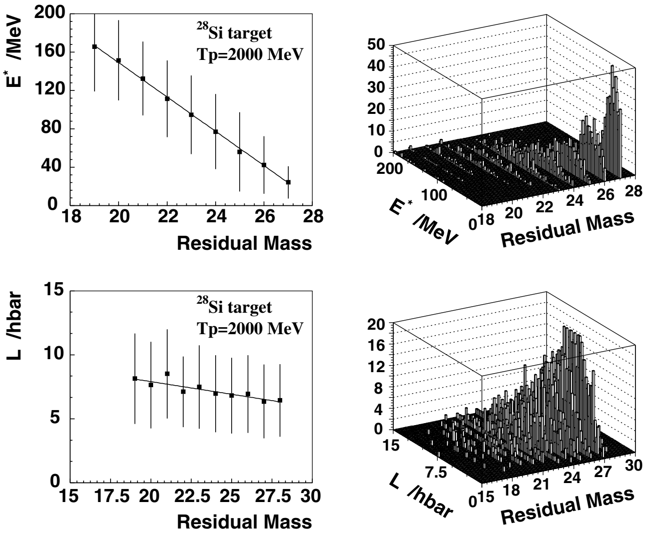

Fig. 5. Two-dimensional correlation plots of excitation energy *versus* residual mass and angular momentum *versus* residual mass, presented as: right, standard two-dimensional histograms; left, as function of regression with imposed vertical bars whose length is twice the standard deviation of the distribution for given value of residual mass.

targets: ^{12}C, ^{28}Si, ^{63}Cu, ^{120}Sn, ^{209}Bi. We have found that the distribution of angular momentum and excitation energy are quite well described by gamma distributions, *i.e.* $f(t) = \frac{1}{x_0^{s+1}\Gamma(s+1)}(t)^s\exp(-t/x_0)$; for $t > 0$; $x_0 = \frac{\sigma^2(t)}{\langle t\rangle}$; $s = \left[\frac{\langle t\rangle}{\sigma(t)}\right]^2 - 1$ (statistical inference tests were performed —fig. 2).

In figs. 3, 4 the results of CBUU simulations are shown. Only average values and standard deviations σ are presented for the distributions of angular momentum and excitation energy, because just these two parameters are needed to present the gamma distribution in an unambiguous way. One finds from the figures that if the number of ejected nucleon DA = Target Mass – Residual Mass increases, the average values of both excitation energy and angular momentum increases as well. There is a very intuitive way to explain it —when more nucleons are ejected, one should treat this as a signature that more nucleons were involved in INC. The more nucleon-nucleon collisions, the larger the part of the (introduced by incoming proton) energy and angular momentum deposited into the residual nucleus. What is more (as seen in figs. 3, 4) the dependency is smooth and linear as a function of DA.

In fig. 5 two-dimensional correlation plots are shown: excitation energy *versus* residual mass and angular momentum *versus* residual mass. One draws the conclusion that it is possible to parametrize the excitation energy and angular momentum taking the residual mass (or the introduced parameter DA = Target Mass – Residual Mass), as independent variable for given target and proton energy. We work now on the parametrization that involves also dependency on the target mass and proton impact energy.

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